DIODE LASER PUMPED FAR-INFRARED LOCAL OSCILLATOR BASED ON SEMICONDUCTOR QUANTUM WELLS

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ABSTRACT

The goal of our research is to generate tunable FIR waves to be used as local oscillators or for other spectroscopic applications. Our approach is to use optically pumped resonant transitions in semiconductor quantum wells. The innovative aspects of this approach include the use of InGaAs/AlAsSb or InAs/AlGaSb quantum well structures, which allow the compact near infrared (NIR, 1.5 microns) diode lasers to be used as pumping, due to the deep conduction band wells in such structures. This approach will eventually lead to compact FIR sources from a few THz up to 10 THz, a frequency range for which it is increasingly difficult to produce local oscillators using electronic means. To demonstrate the feasibility of our approach, we have conducted extensive theoretical investigation of THz generation using both optically pumped laser scheme and double-resonance difference-frequency generation (DFG) scheme. We show that large enough optical gain or nonlinear optical coefficient can be achieved in these structures.

INTRODUCTION

FIR local oscillators (LOs) are important for heterodyne detection scheme used in FIR astronomy and other earth science related measurements[1]. FIR LOs based on electronic means are typically restricted to the lower end of the THz range, while the molecular lasers that can provide higher THz range wavelengths are inefficient and bulky. On the other hand semiconductor based optical devices are known for their high efficiency and compact size. With the increasing spectral coverage of semiconductor lasers and other semiconductor based nonlinear optical devices, it was quite natural that people started pursuing the FIR generation using semiconductors. Progress in this regard has been quite remarkable in the last few years, as represented by the recent demonstration of quantum cascade lasers operating at 24 microns in wavelength.

One of the promising semiconductor based approaches is the optically pumped FIR lasers or difference frequency generation (DFG) using CO_2 laser as pumping sources.[2,3,4] While such approaches are typically based on GaAs material system and thus have the advantage of working with mature material growth technology, the required CO_2 lasers make the final system bulky. In our approach, we pursue a purely semiconductor based, and therefore potentially miniaturized, technology for the FIR generation. Since most of the mature semiconductor lasers are in the NIR range (around 1.5 microns), this approach requires the use of semiconductor structures that have a conduction band quantum well deep enough (over 1 eV) to allow the NIR laser pumping between different subbands. We have theoretically studied three material systems: 1) InGaAs/AlAsSb/InP system, 2) InAs/AlGaSb, and 3) GaAs system based on the excitonic pumping. Each of the three material systems allows NIR pumping and enough optical gain can be achieved for optically pumped FIR laser operation. We also studied the possibility of DFG in the first material system to demonstrate that large second order optical nonlinearity can be achieved. Experimental efforts in demonstrating some of the approaches are currently underway in collaboration with Rice University and will be reported elsewhere.

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OPTICAL PUMPED INTERSUBBAND THz LASER

Optically pumped intersubband lasers have been successfully demonstrated[2] for wavelengths up to 15.5 microns. Terahertz spontaneous emission of 8 THz in frequency has also been measured[3] with CO_2 laser pumping of the GaAs-based quantum wells. In our theoretical study, we consider the optical gain in a different material system characterized by a very deep (around 1.7 eV) conduction band quantum well. The structure, shown in Fig.1, consists of one $In_{0.53}Ga_{0.47}As$ quantum well coupled with two InP wells with $AlAs_{0.56}Sb_{0.44}$ as barriers. The structure is modulation doped and under a DC field of 25kV/cm. Our theory[4] takes into account the Hartree-Fock interactions of electrons in the well, and the non-parabolic effects of the conduction bandstructure. As shown in the figure, the deep InGaAs quantum well leads to an energy separation of states 1 and 4 of 0.81 eV (1.53 microns), which corresponds to the commercially available telecom laser wavelength. Furthermore, the pumping laser and the terahertz module, being both based on InP technology, can be integrated, potentially monolithically.

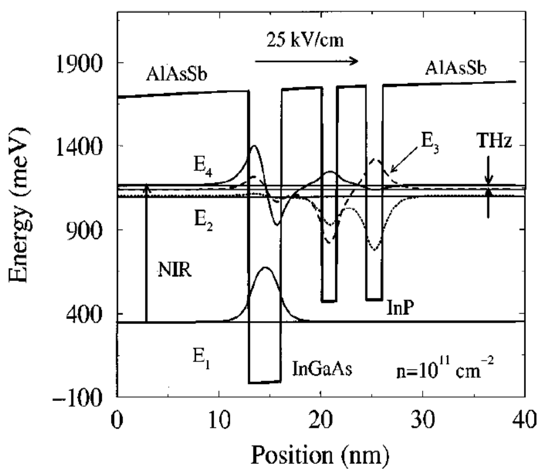


Fig.1 Bandedge profile and energy levels of modulation doped InGaAs/AlAsSb/InP quantum well structure under DC field (see Ref[4] for details.

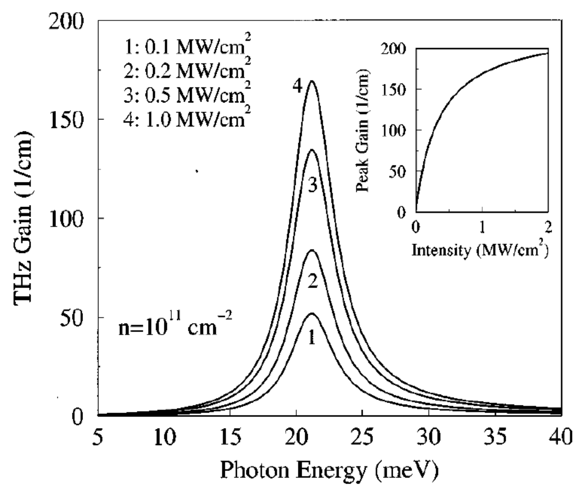


Fig.2 Optical gain for the quantum structure shown in Fig.1 under NIR pumping at 4 different levels.

Fig.2 shows the optical gain between subbands 4 and 3, when an NIR laser pumps the 1-4 transition. We see the gain spectrum peaks at 20 meV, which corresponds to a frequency of about 5 THz. The maximum gain reaches 170 1/cm at the pumping level of $1MW/cm^2$, which is reasonable at this wavelength. The optical gain can be increased further by optimizing the quantum well structure and by increasing the pumping intensity.

DOUBLE-RESONANT DIFFERENCE-FREQUENCY GENERATION

While a THz semiconductor laser has many obvious advantages over other incoherent oscillators, the requirement for population inversion in intersubband structures makes such a laser difficult to achieve.

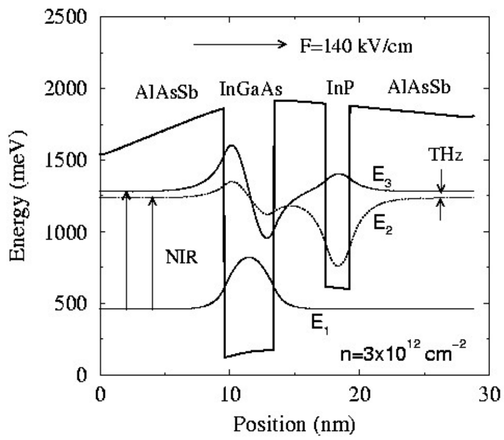


Fig.3: Bandedge profile and energy levels of modulation doped InGaAs/AlAsSb/InP quantum well structure under DC field, designed for DFG scheme.

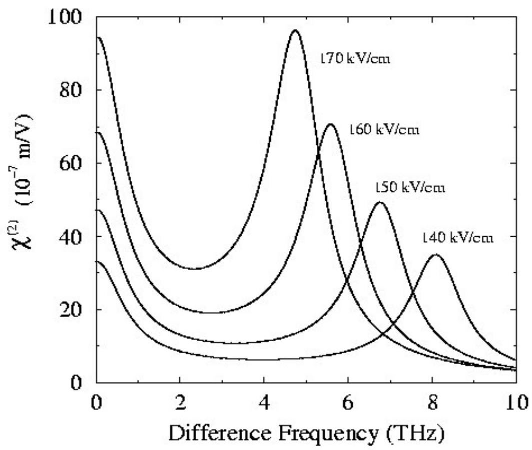


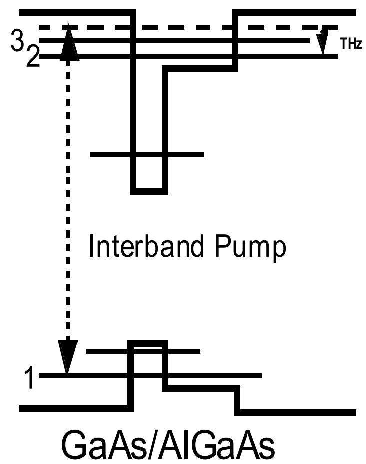
Fig.4: Second order nonlinear optical coefficient under different DC bias levels, showing the large nonlinearity and tenability.

As an alternative, other nonlinear optical generations have also been pursued. Notably the DFG scheme has been demonstrated in GaAs based quantum well structures for generation of long wavelength IR[7] and terahertz wave[6] using two IR lasers. We pursued the DFG scheme in the deep InGaAs/AlAsSb/InP quantum wells using a three-subband structure as shown in Fig.3. The corresponding optical nonlinearity is shown in Fig.4, where we see that the optical nonlinearity is orders of magnitude larger than that achievable in bulk GaAs, due to the large dipole moments for the z-polarized field and to the resonant enhancements of the transitions. Another feature we see is that the peak position of the chi-2 can be tuned very sensitively by the applied DC field with a tuning range of a few THz.

EXCITON-STATE PUMPING SCHEME

Another attractive possibility of optical pumped THz generation is to utilize strong optical response at the exciton resonance. There are several advantages of using this approach. In a scheme using optical pumping of interband continuum states, there are two serious issues. The first one is the broad linewidth of the interband transitions due to the opposite curvatures of conduction and valence bands, which lead to the inhomogeneous frequency distributions and the associated broadening. This broadening is typically at the order of ten, or a few tens of, THz, larger than the center frequency of the oscillation to be generated. Another issue is the poor selectivity of pumping states. As a result, all the upper subbands are more or less equally populated, making the population inversion difficult. Compared to the continuum state pumping, excitonic state pumping avoids both of these issues. And more importantly, the exciton state pumping allows the normal incidence of the pumping lasers and the use of mature materials such as GaAs, yet retaining the advantages of IR pumping lasers.

Fig. 5 shows the results of our theoretical study. The left panel shows the step quantum well structure based on GaAs/AlGaAs. The step quantum well serves two purposes: First it allows easy wavelength design by changing the Al-content in the step region. Second, the strong coupling between the second and third states provides strong interaction of pumping laser with the 1-3 transition. In the two figures (a, and b) of the right panel, we show optical gain as function of the probe frequency at 77K. In figure 5(a), we show the effects of pumping detuning with respect to the empty state separation between states 1 and 3. Maximum gain is achieved with a detuning of –10 meV, which corresponds to the binding energy of this excitonic transition. As the pumping laser is moved away from the excitonic resonance, the gain decreases rapidly. Since exciton linewidth is a very sensitive quantity, we show in Fig.5 (b) how this quantity affects optical gain. As linewidth increase from 1 meV to 3 meV, we see optical gain decrease by about two thirds. In the case of 3meV linewidth, we still obtain quite significant optical gain, larger than that obtainable in the case of intersubband pumping (see Fig. 2).



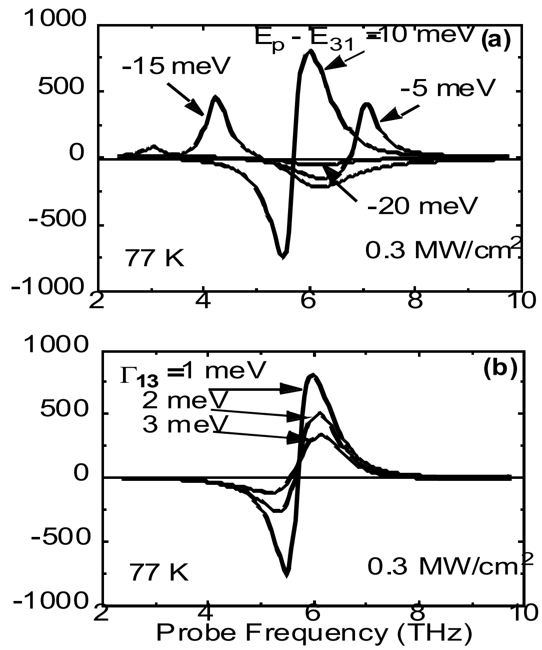


Fig.5 Schematics of a THz generation based on interband excition state pumping of a GaAs step quantum well structure (left) and the corresponding gain spectrum (right, a and b).

In summary, we have performed a series of studies on NIR laser pumped THz generation using intersubband transitions in deep quantum wells and using interband excitonic transitions in GaAs quantum wells. In either of the laser schemes studied, enough optical gain can be achieved to realize THz laser operation in an optimized optical cavity. In the DFD scheme, we show that giant second order optical nonlinearity can be achieved due to the resonant nature of the transitions and due to the large dipole transition elements for the TM polarized light field. Experimental realization of some of the schemes is under investigation and will be reported in the future.

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